NOνA Physics Update: PAC and After

NOνA Collaboration Meeting

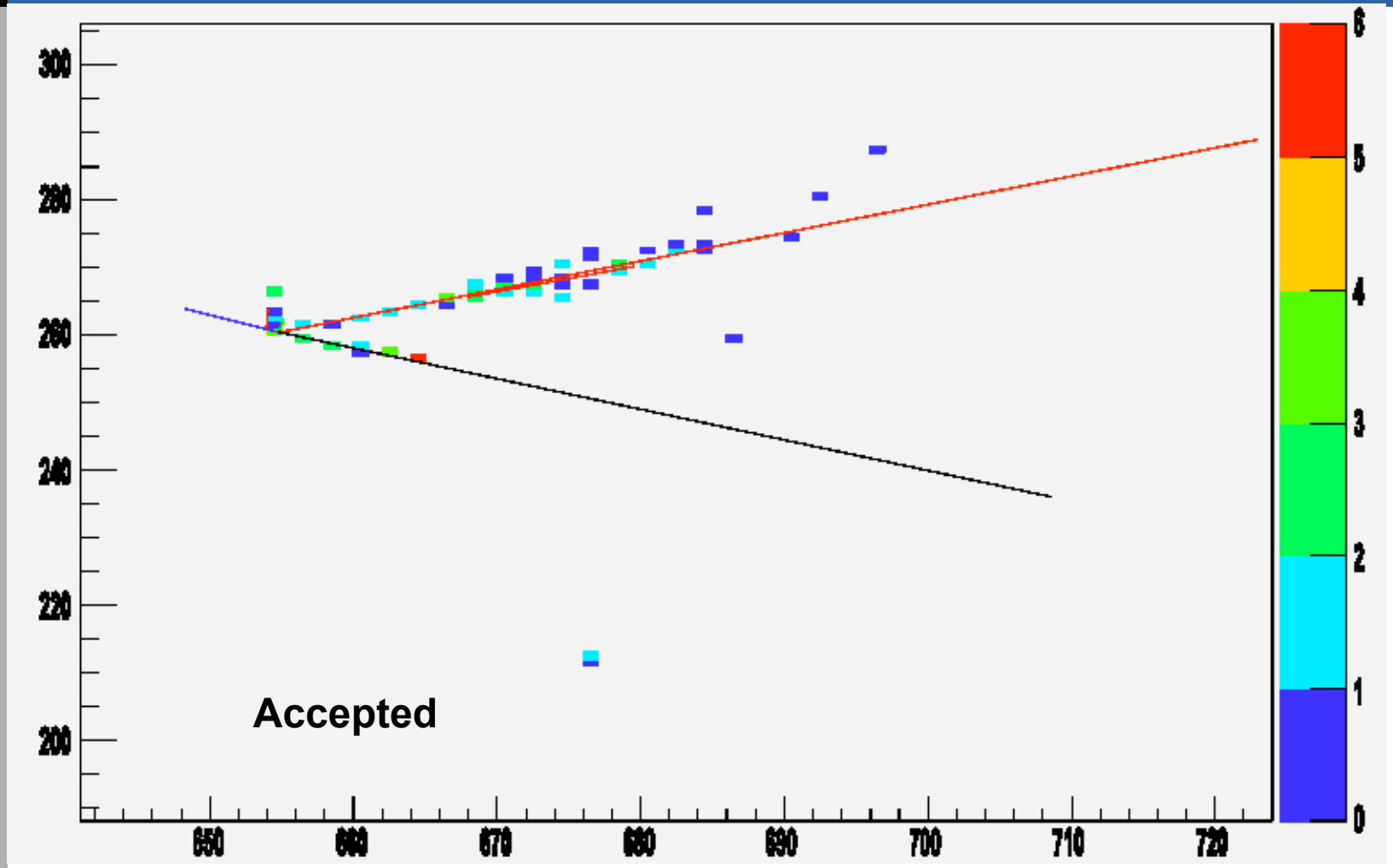
Fermilab

5 May 2005

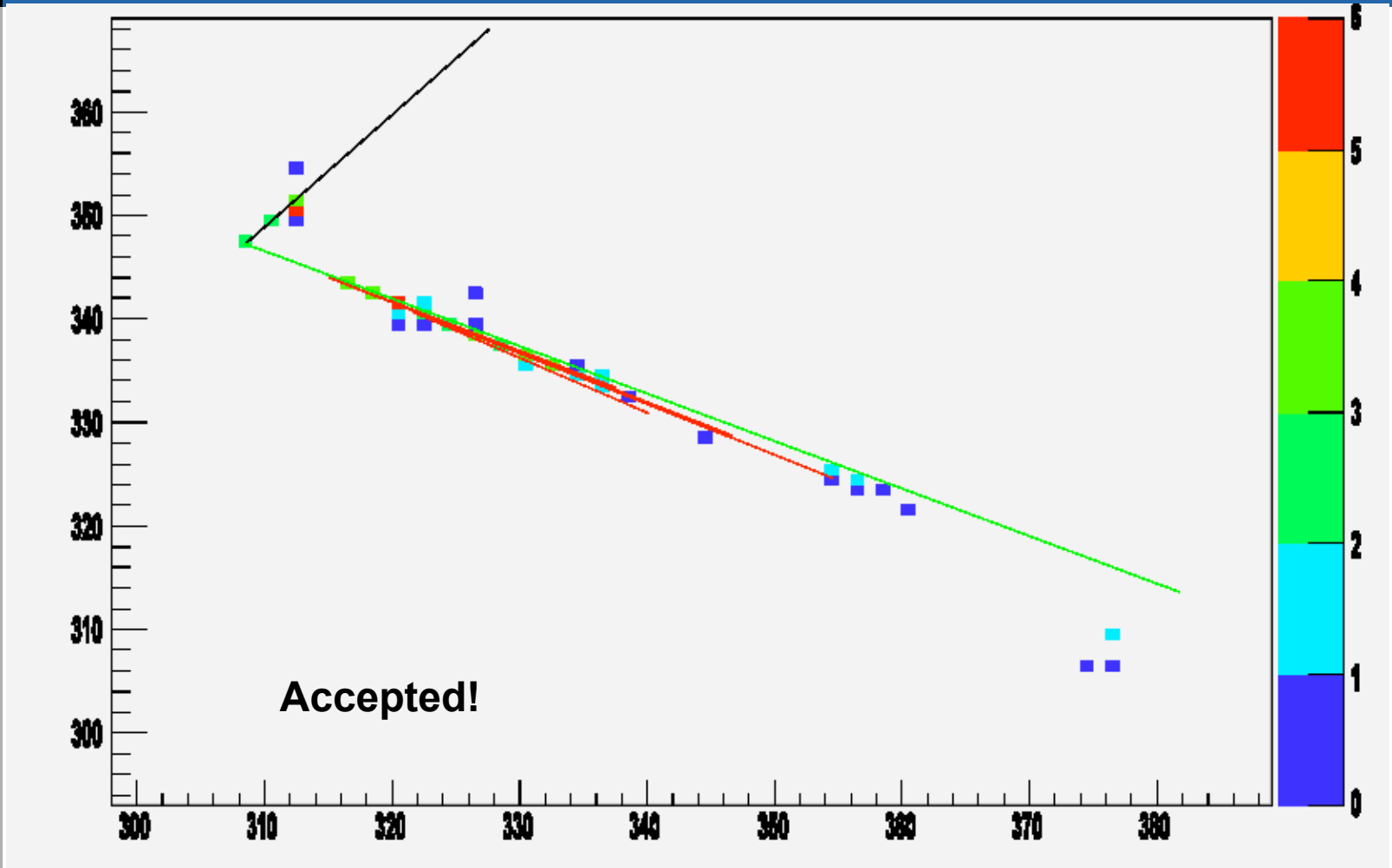
Gary Feldman

Aside: Construction at Harvard

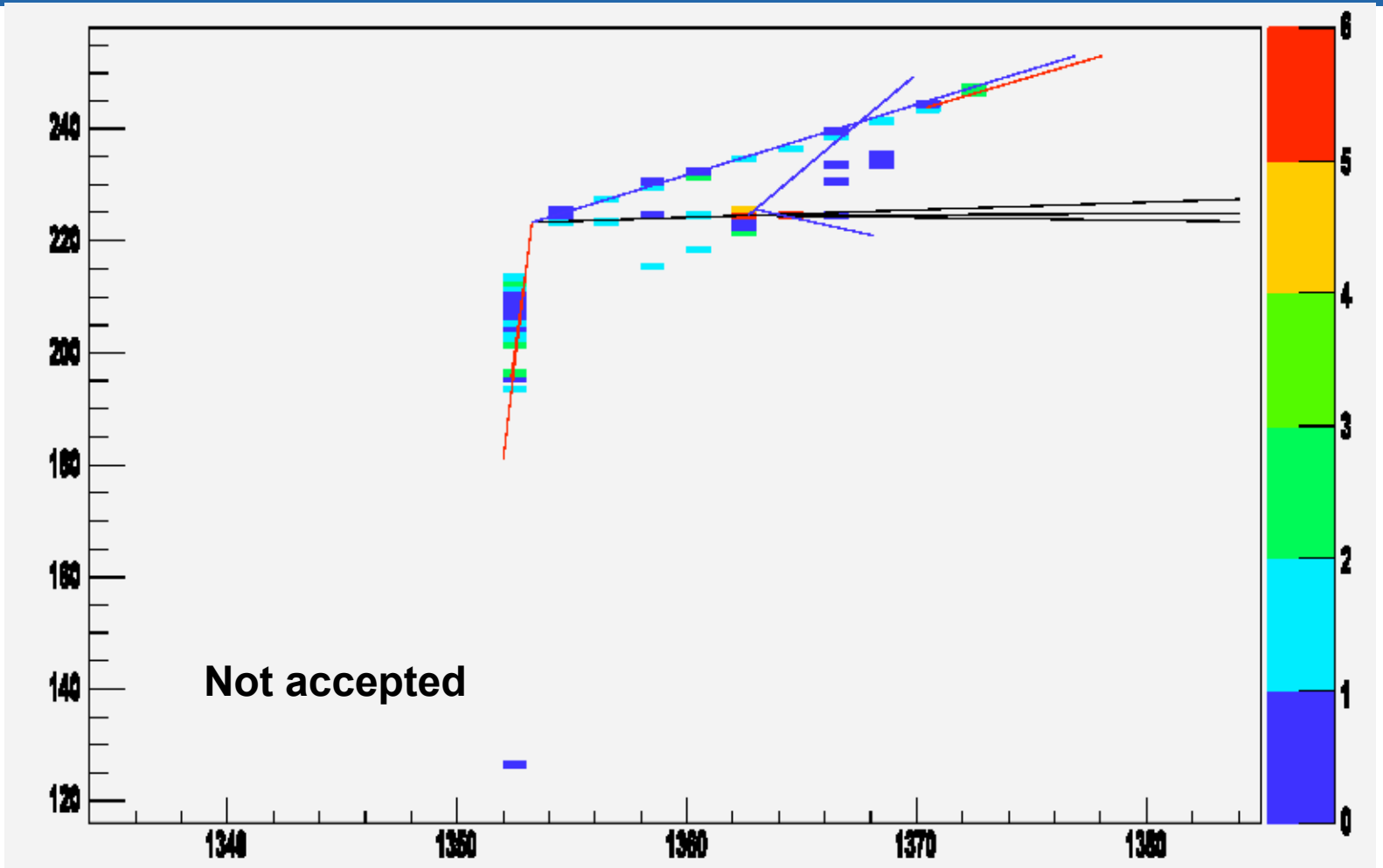
1.87 GeV $\nu_e N \rightarrow e p \pi^+ \pi^0$ x-z View



2.11 GeV $\nu_\mu N \rightarrow \nu_\mu p \pi^0$ x-z View



1.86 GeV $\nu_e N \rightarrow e p \pi^+$ x-z View



Post-Collider Proton Plan

- **Proton Plan with Collider**
  - 9/11 Slip-stacked Booster batches at 5.5×10^{12} p/batch
  - Repetition rate = 0.8 s (Booster) + 1.4 s (Ramp) = 2.2 s
  - 10% for Collider shot setup + 5% for antiproton transfer
  - $\Rightarrow$ 3.4 $\times10^{20}$ protons/yr
- **Post-Collider Proton Plan**
  - 11 batches for neutrinos $\Rightarrow$ 11/9 = 1.22 factor
  - Hide Booster filling time in Recycler $\Rightarrow$ 0.8 s $\rightarrow$ 0.067 s
    $\Rightarrow$ 2.2 s $\rightarrow$ 1.467 s = 1.50 factor
  - Save 10% shot setup and 5% antiproton transfer = 1.17 factor
  - $\Rightarrow$ (3.4 $\times10^{20}$ protons/yr)(1.22)(1.50)(1.17) = (7.3 $\times10^{20}$ protons/yr)
- **Negotiated rate is 90% of this: (6.5×10^{20} protons/yr)**
- **Proton Driver rate taken as 25×10^{20} protons/yr**

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

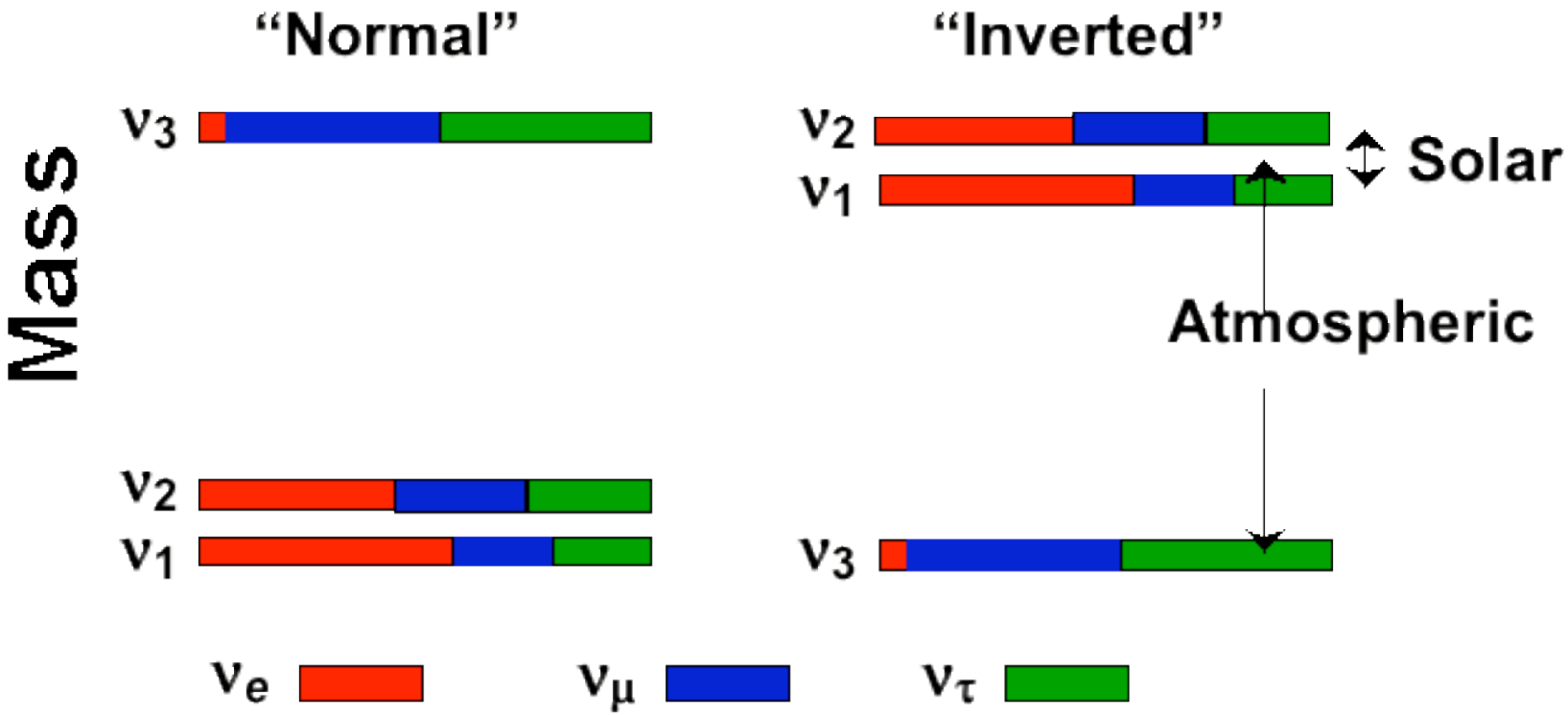
- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  } Atmospheric-solar interference

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

Mass Ordering



$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

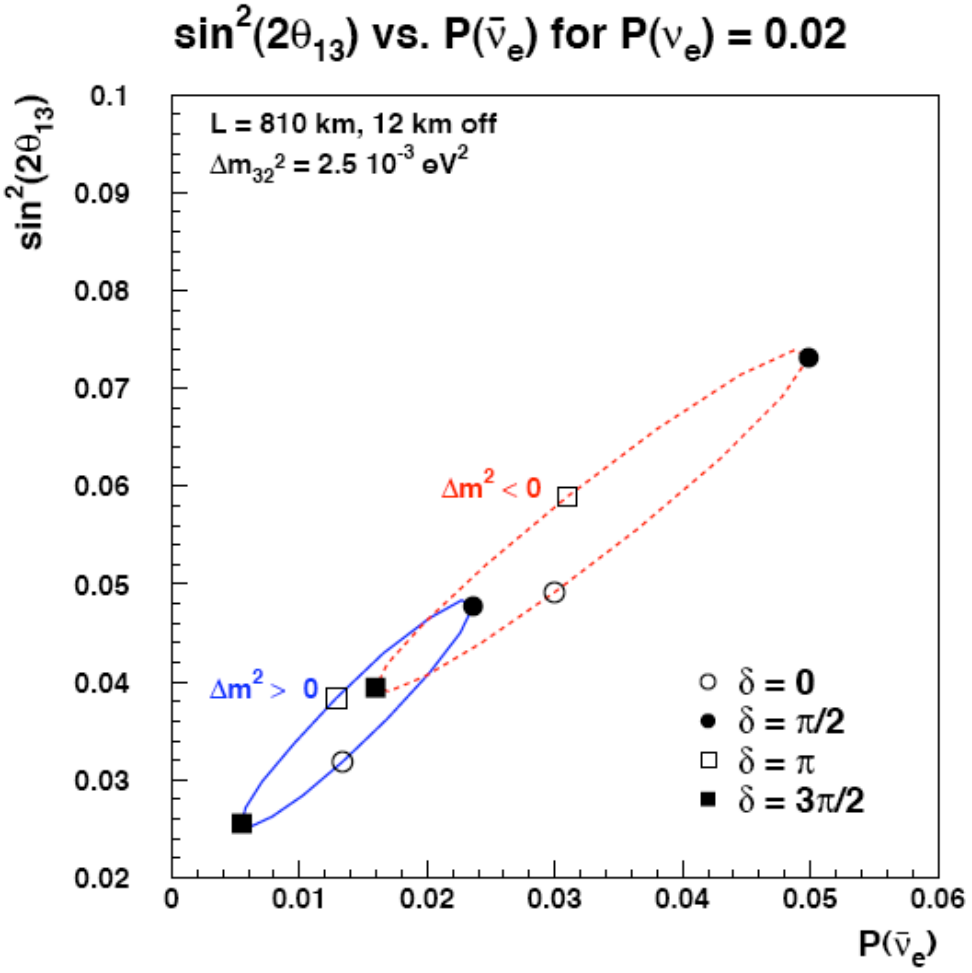
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11\,\text{GeV}$$ for the earth's crust.

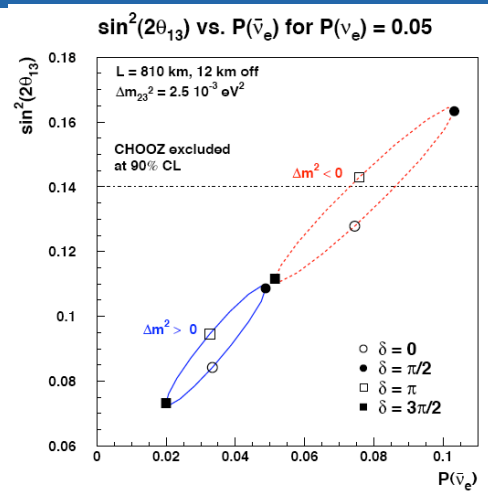
About a ±30% effect for NuMI, but only a ±11% effect for JPARC .

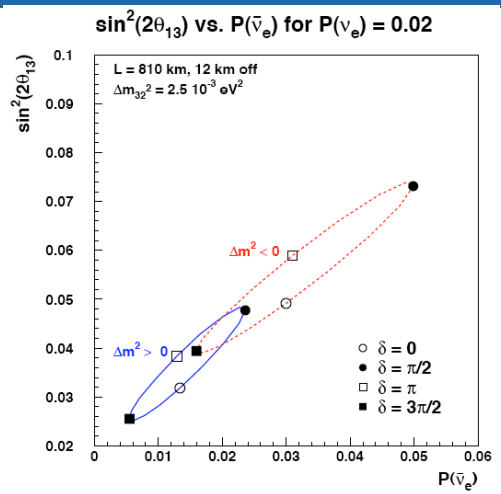
However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

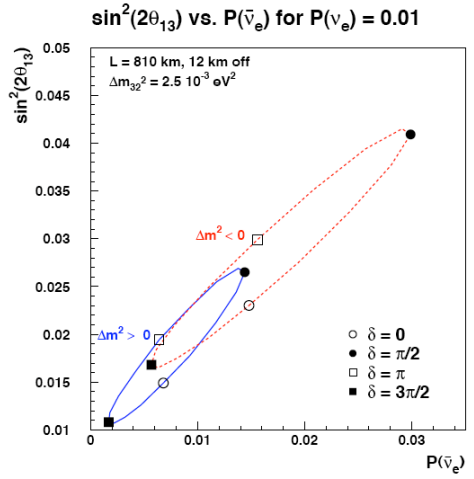
Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation

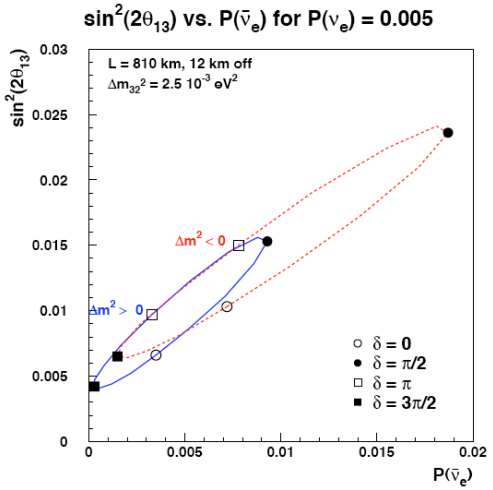


Parameters Consistent with Other Oscillation Probabilities







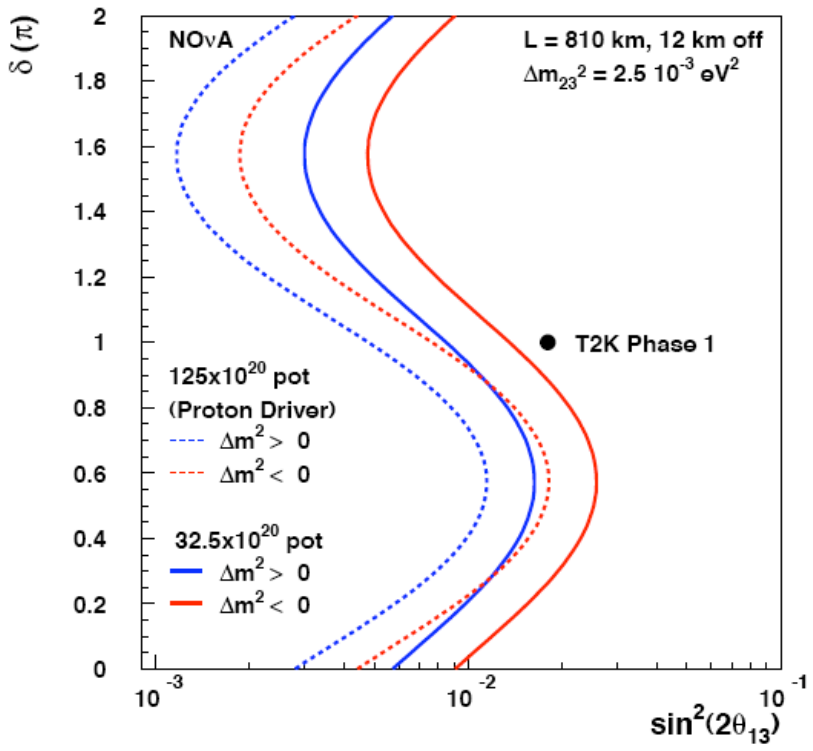


Proposal Background Error

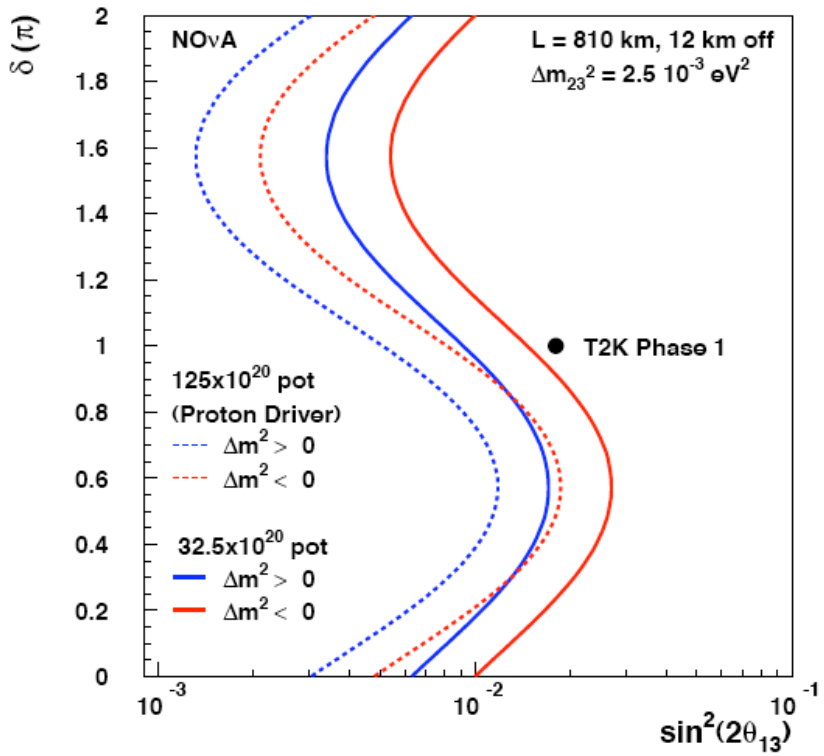
- While reconciling my calculations with those of Walter Winter and Patrick Huber, I discovered that I had inadvertently failed to increase the backgrounds from 25 kT to 30 kT, or 16.25 events to 19.5 events -- an error of 0.65 events/year.
- Correcting this error decreases our sensitivity by between 5 and 14% for the pre-Proton Driver data and between 3 and 13% for the Proton Driver data.
- Our most sensitive regions have the largest decrease in sensitivity and the least sensitive regions have the smallest decrease.

3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$

5 year ν run



Plot shown to the PAC



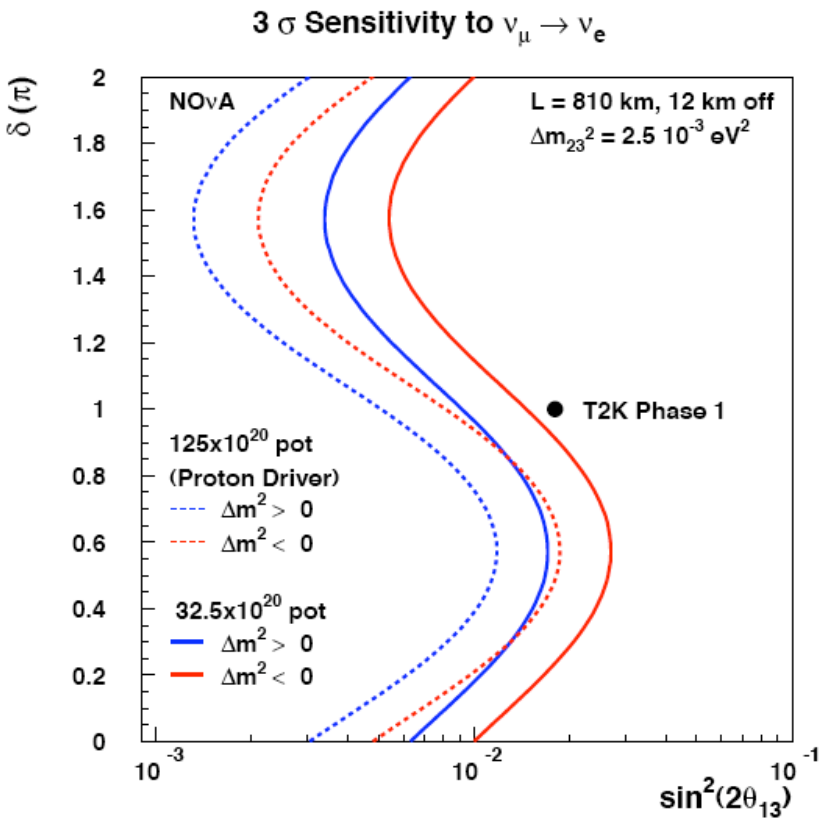
Corrected Plot

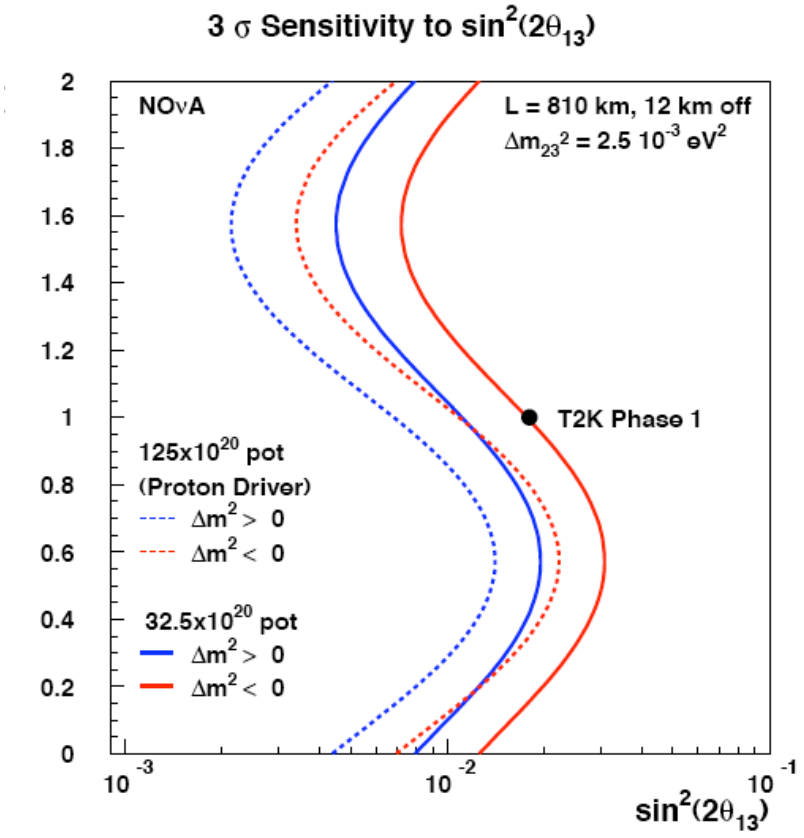
Sensitivity to What?

- The title of the previous plots was "3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$."
- This is not what we want, because we know that $\nu_\mu \rightarrow \nu_e$ exists from the KamLAND experiment.
- What we really want to know is the "3 σ Sensitivity to $\theta_{13} \neq 0$." The difference is the direct solar term which is 0.48 events/year in NOνA.
- This changes the previous plot by 14 to 33% for the pre-PD curve and by 19 to 62% for the PD curve.

3 σ Sensitivity to $\sin^2(2\theta_{13})$

5 year ν run

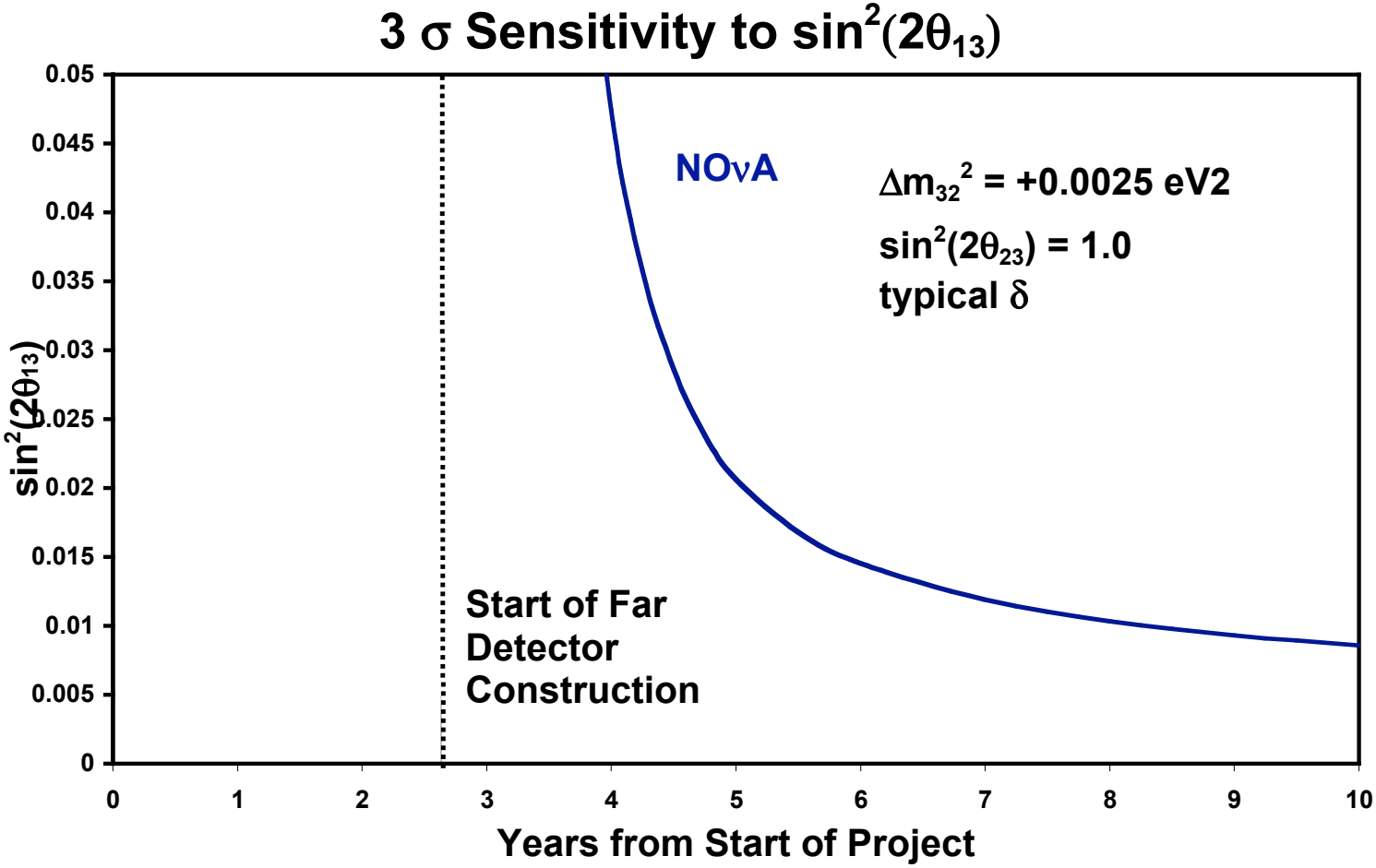




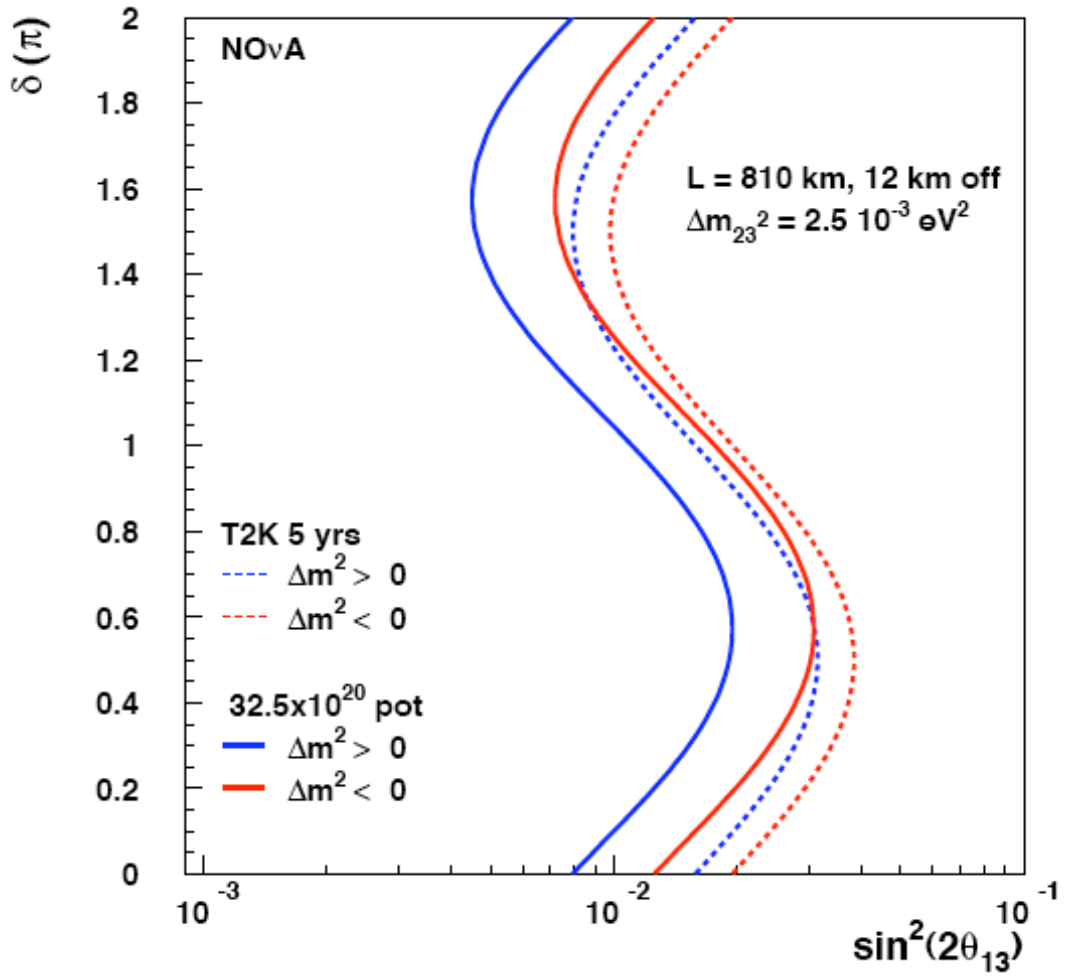
Amusing Factoid

- For NOνA, assuming only ν runs and integrating over the narrow band spectrum, for every value of $\sin^2(2\theta_{13}) < 0.005$ there exists at least one value of δ such that $\theta_{13} \neq 0$ cannot be established regardless of statistics because the interference term exactly cancels the atmospheric term.
- "Solution" to this problem will follow shortly.

Sensitivity to $\sin^2(2\theta_{13})$ vs. Time

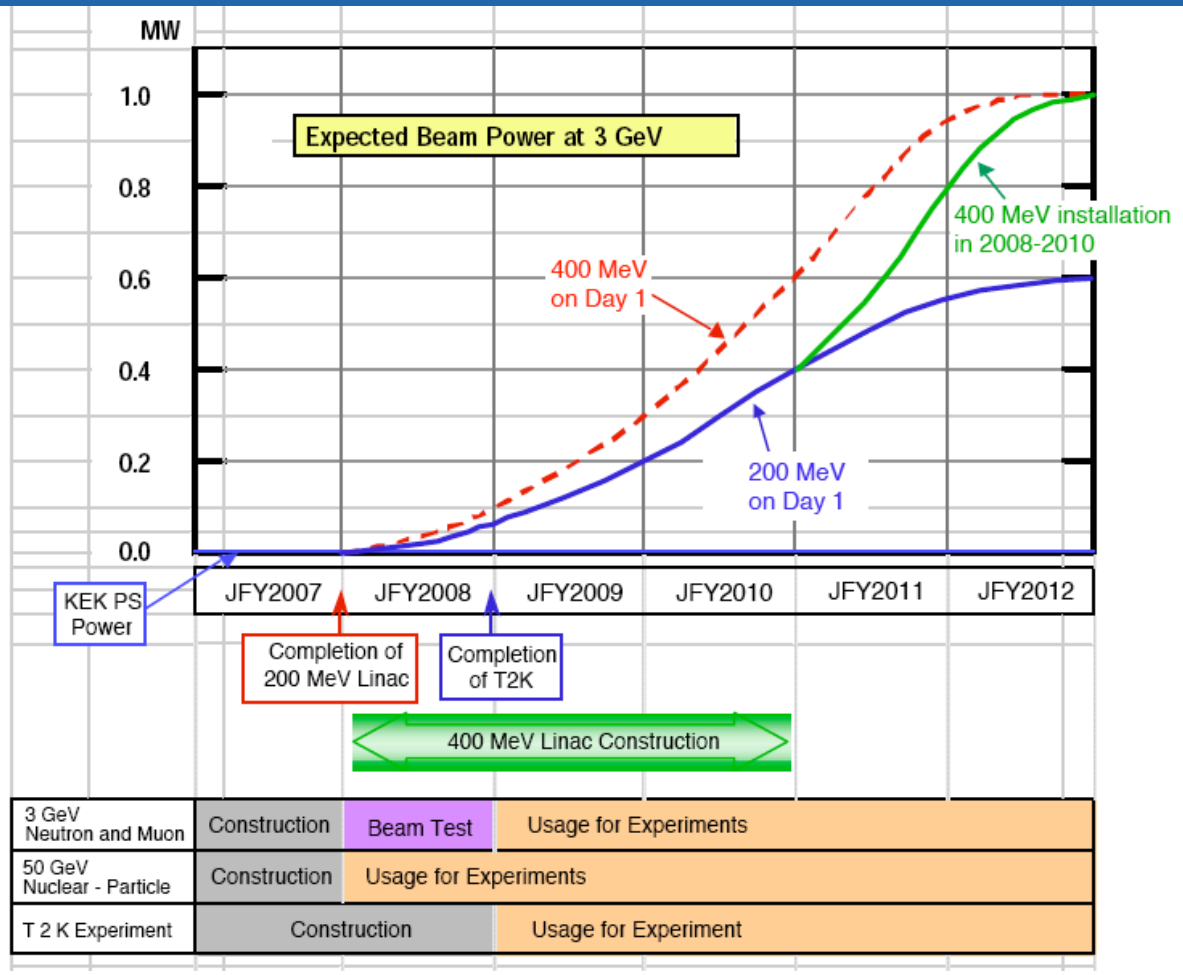


3 σ Sensitivity to $\sin^2(2\theta_{13})$ Comparison to T2K



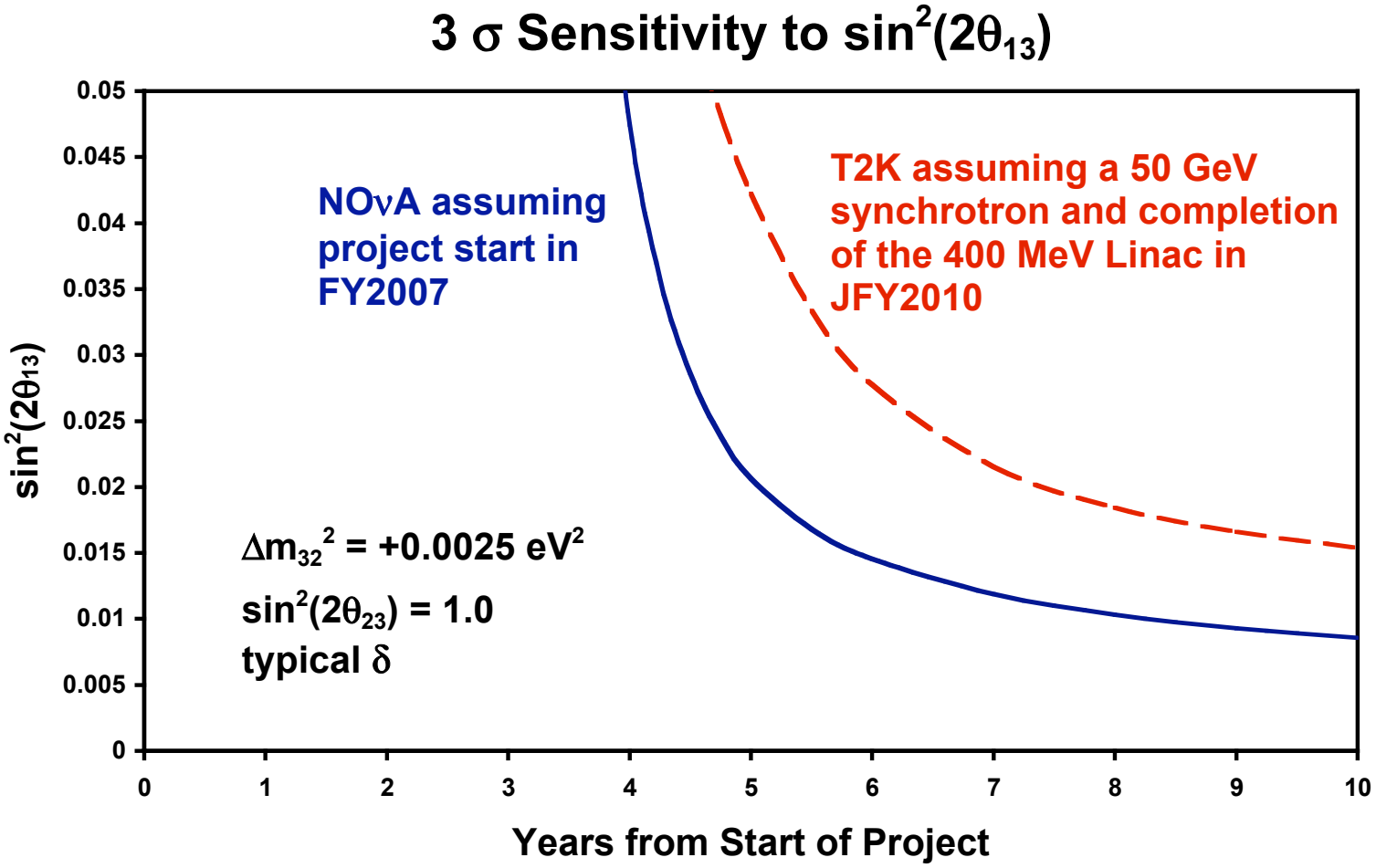
NOνA's sensitivity is greater than T2K's by
1.6 to 1.8 for $\Delta m^2 > 0$
1.3 to 1.4 for $\Delta m^2 < 0$

Assumed T2K Beam Power vs. Time

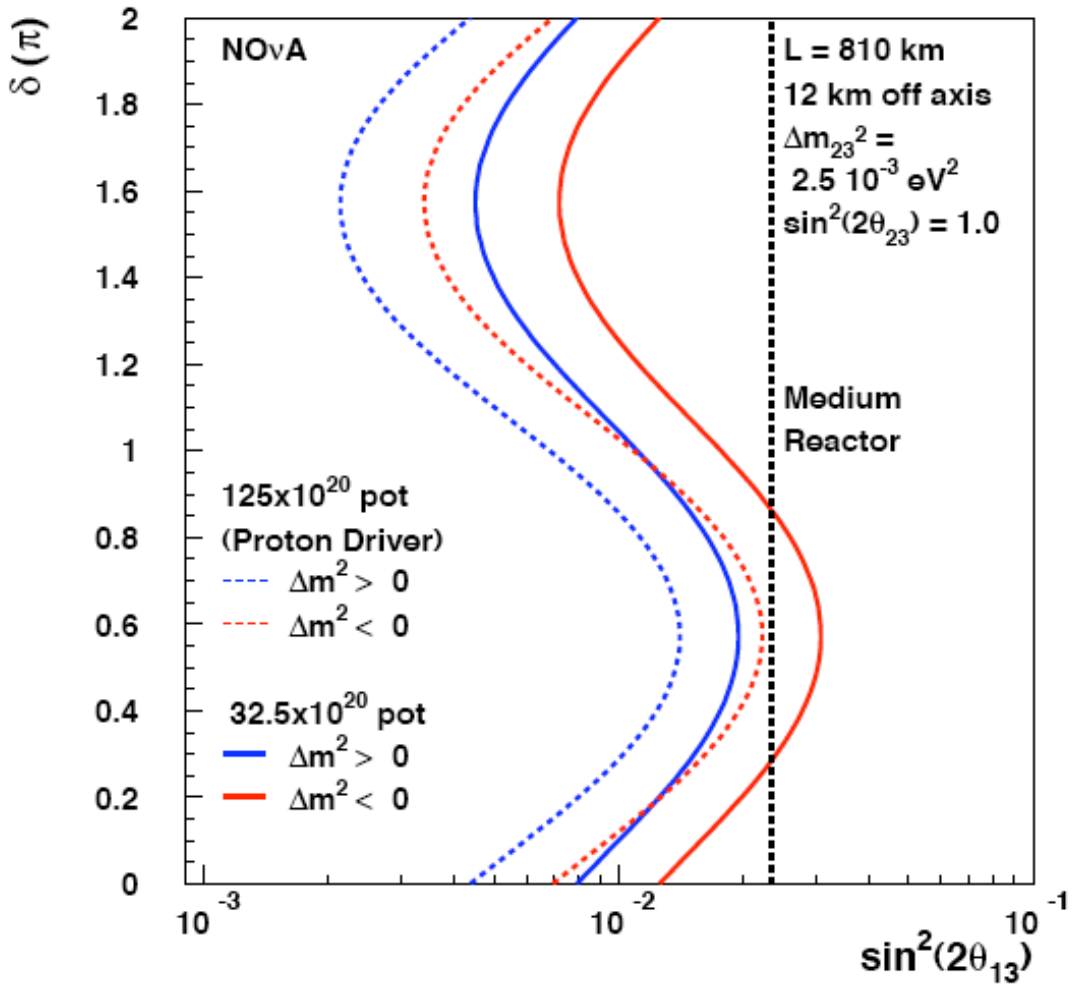


From S. Nagamiya, Feb 2005

Sensitivity to $\sin^2(2\theta_{13})$ vs. Time



3 σ Sensitivity to $\sin^2(2\theta_{13})$ Comparison to Reactors



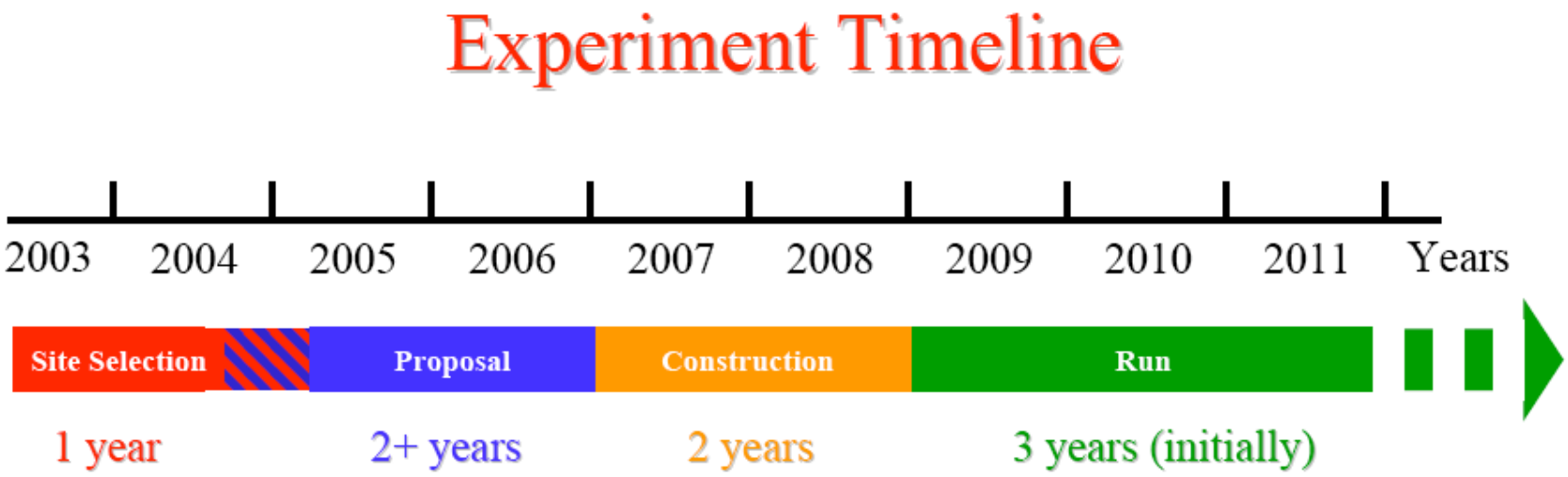
"Medium Reactor" is a Braidwood or Daya Bay class experiment (1% sensitivity at 1.28 σ ("90% CL")

NOνA's sensitivity is greater than that of a medium reactor by

1.2 to 5.2 for $\Delta m^2 > 0$

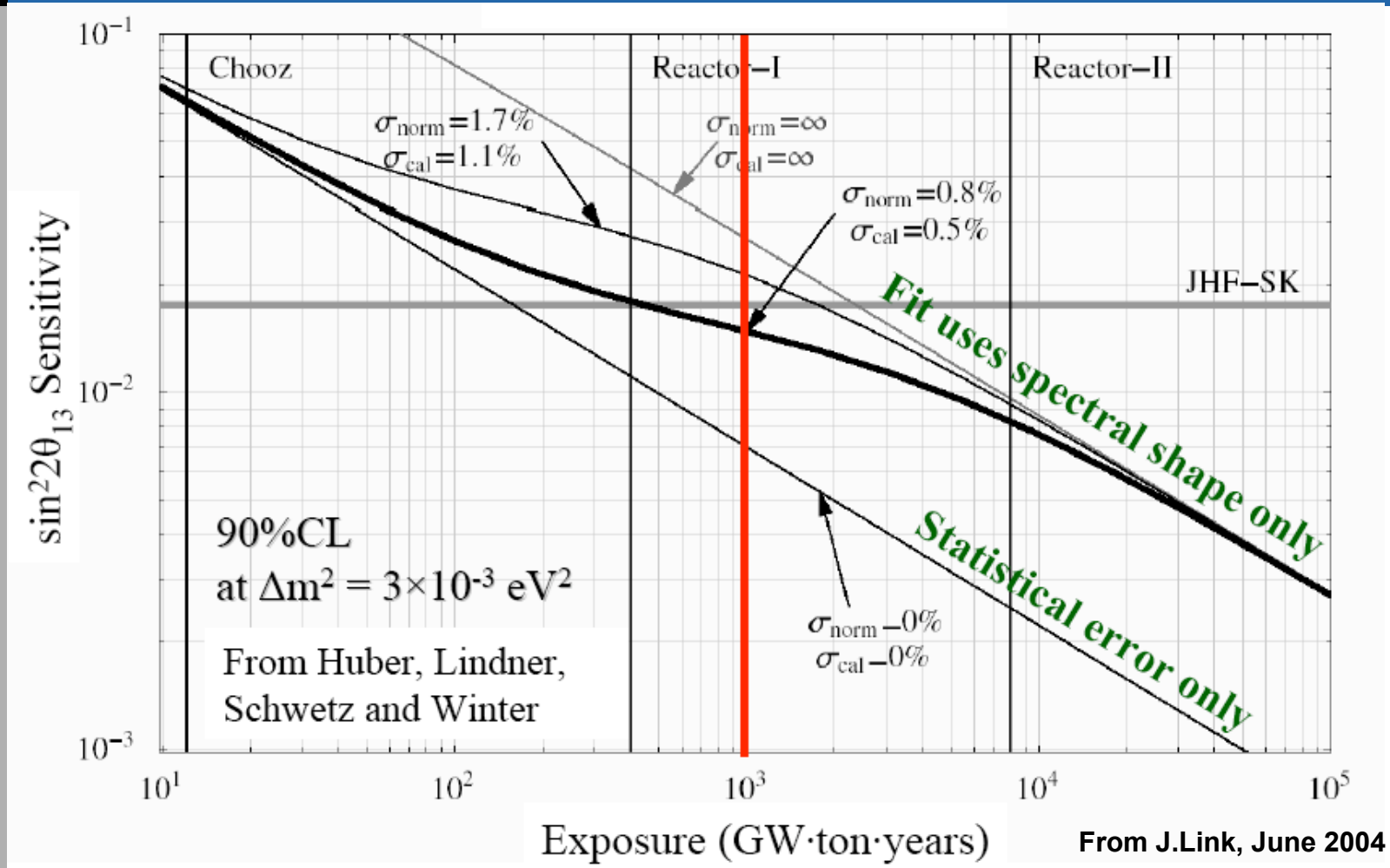
0.8 to 3.2 for $\Delta m^2 < 0$

Assumed Reactor Timeline



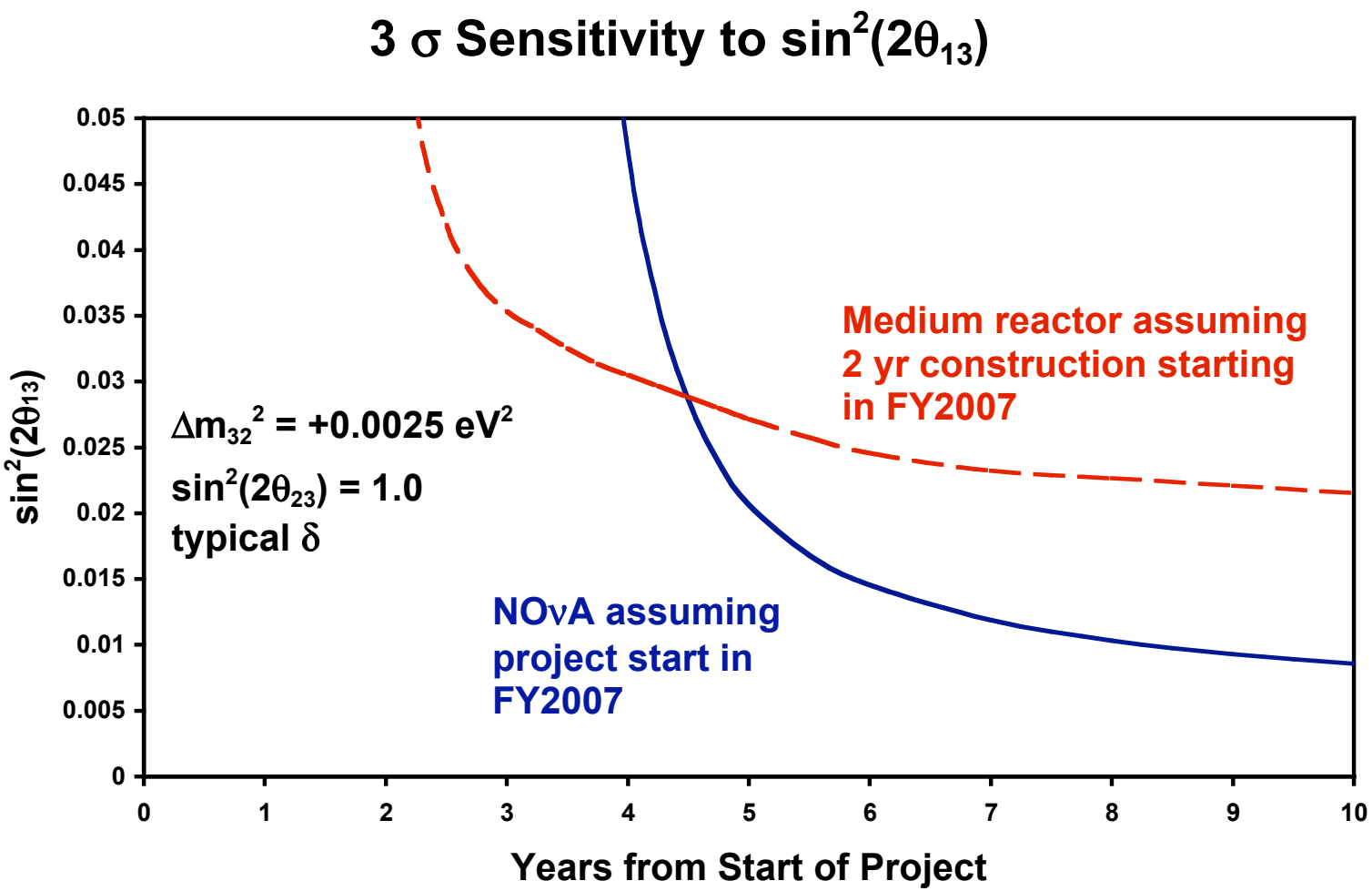
From J.Link, June 2004

Reactor Sensitivity Model with 900 GW tons/yr

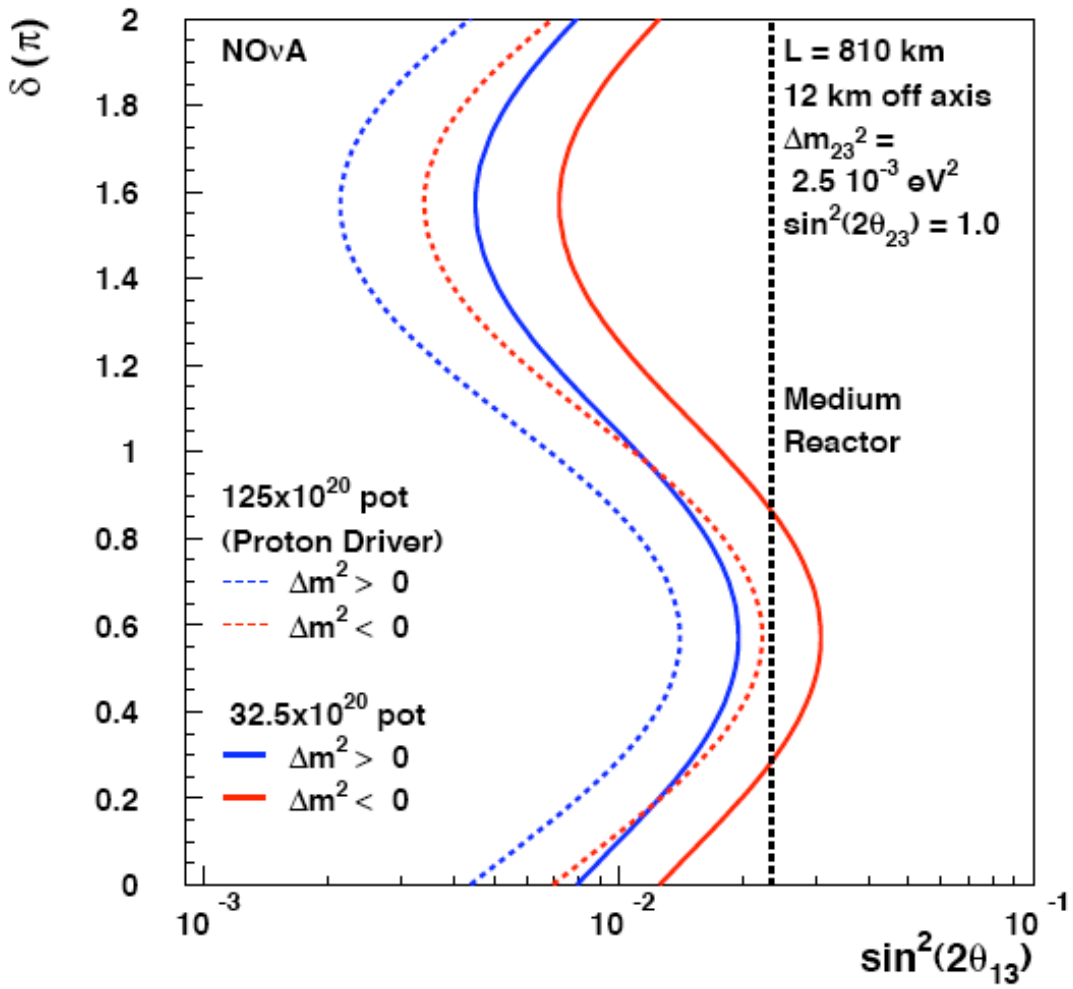


From J.Link, June 2004

Sensitivity to $\nu_\mu \rightarrow \nu_e$ vs. Time



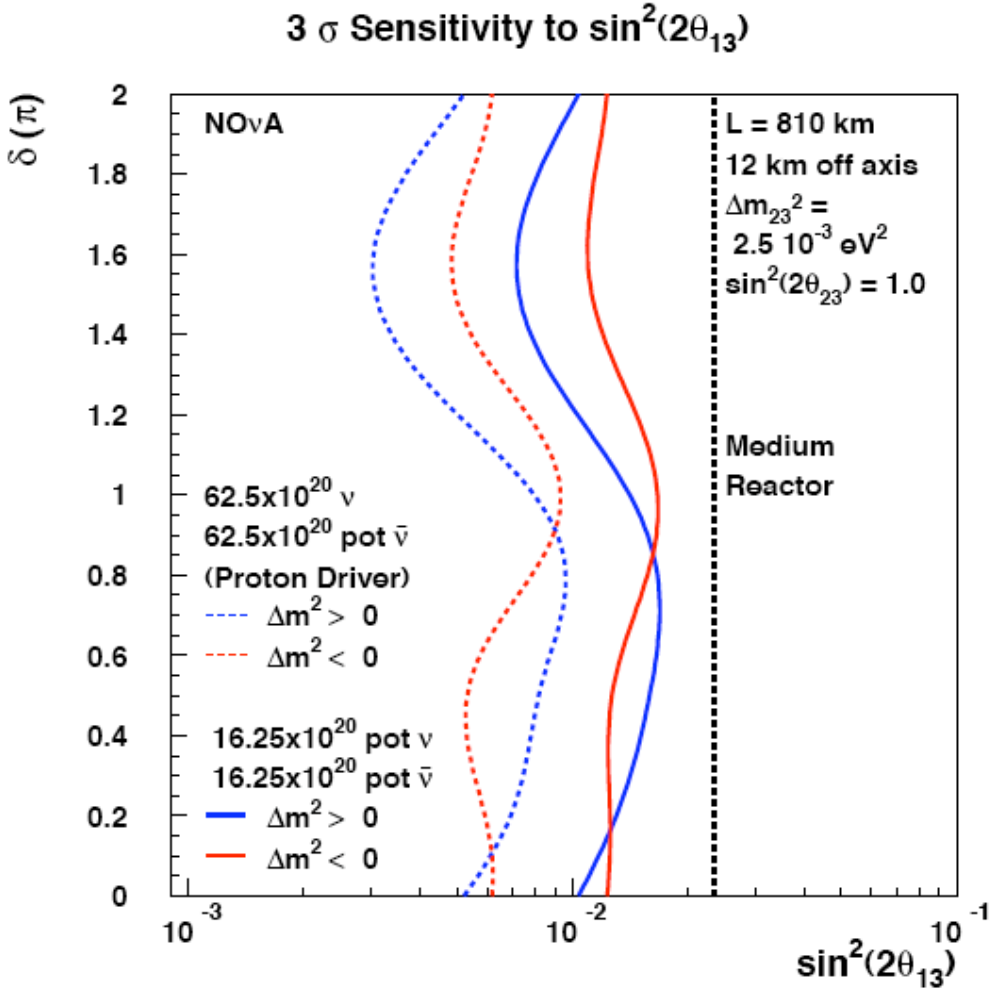
What's Wrong with this Picture?



(1) There is no theoretical reason to favor $\delta > \pi$ over $\delta < \pi$.

(2) There is no reason why NOνA should be inferior to a reactor experiment anywhere.

Solution: Split Time between Neutrinos and Antineutrinos



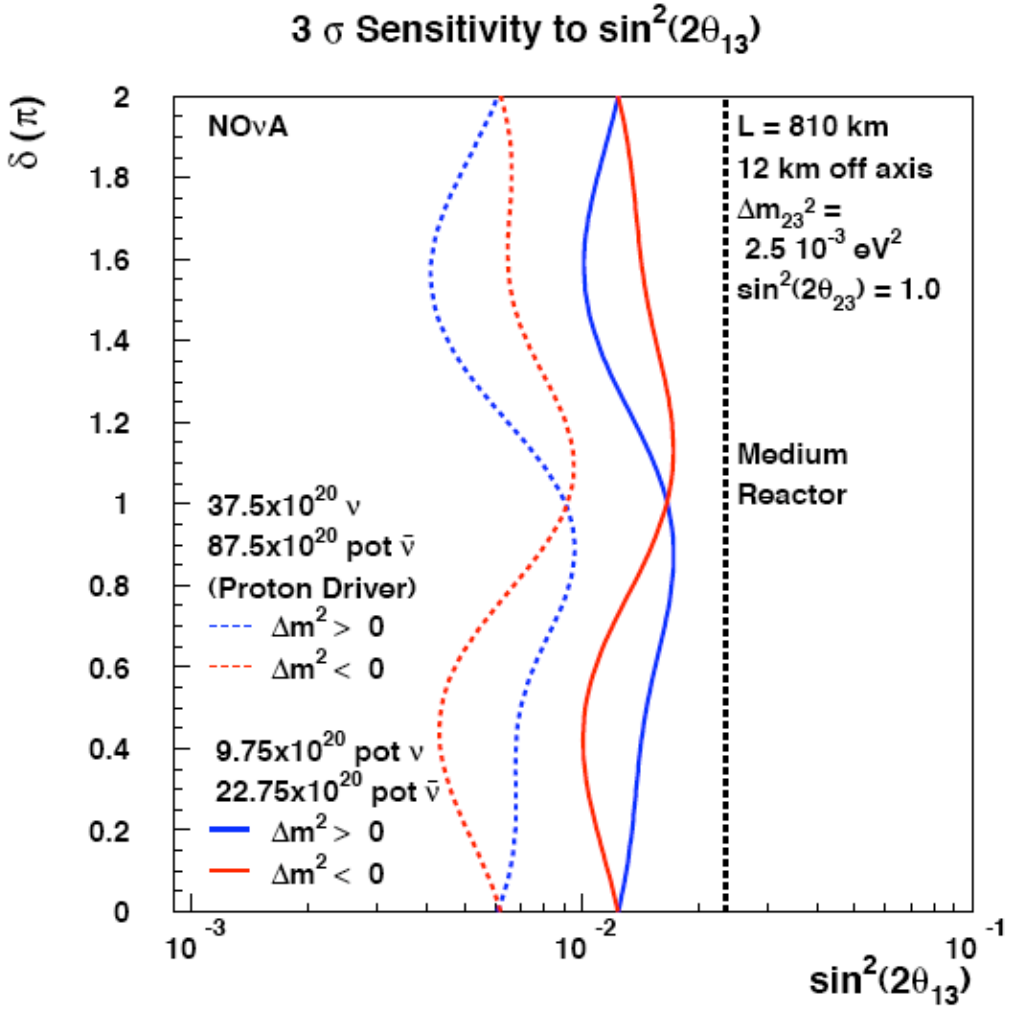
2.5 yr each neutrinos and antineutrinos

Now NOνA's sensitivity is greater than that of a medium reactor by

1.4 to 3.3 for $\Delta m^2 > 0$

1.4 to 2.1 for $\Delta m^2 < 0$

Another Option: 1.5/3.5 year Neutrino/ Antineutrino Split



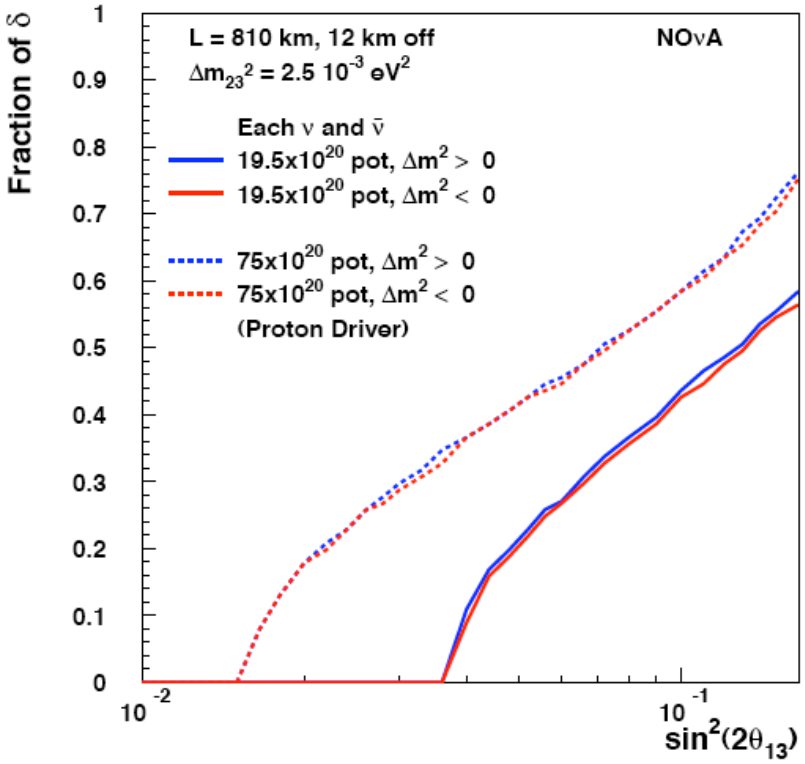
Now NOνA's sensitivity is greater than that of a medium reactor by

1.4 to 2.3 for $\Delta m^2 > 0$

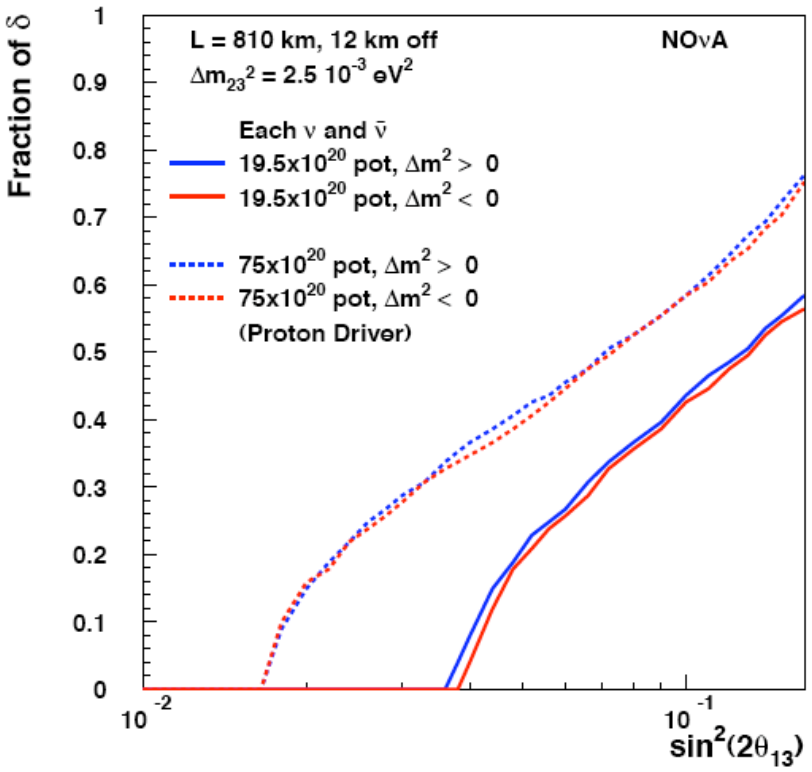
1.4 to 2.3 for $\Delta m^2 < 0$

2 σ Resolution of the Mass Hierarchy

3 years each ν and ν–bar runs

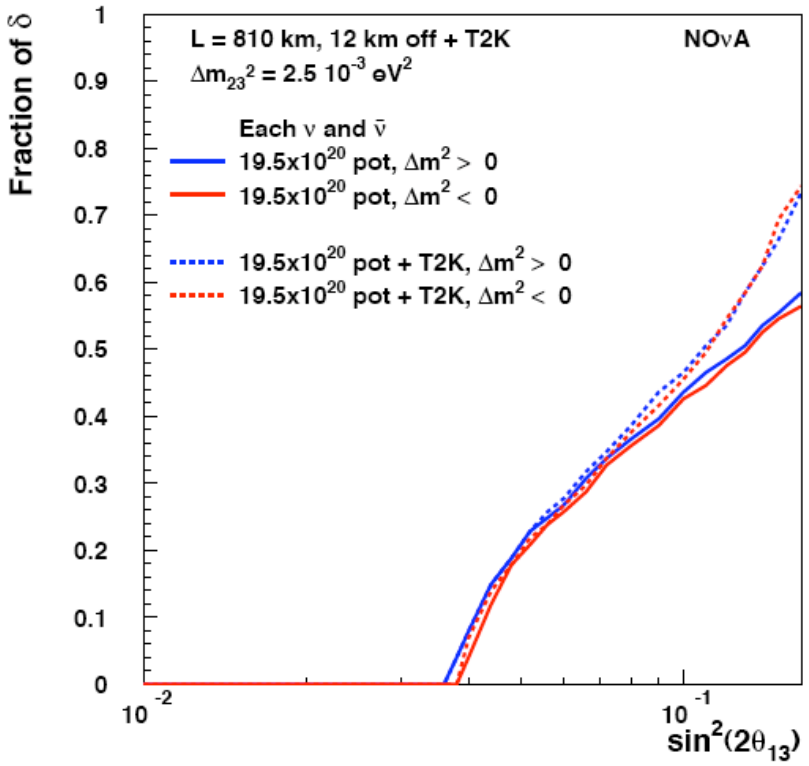


Plot shown to the PAC

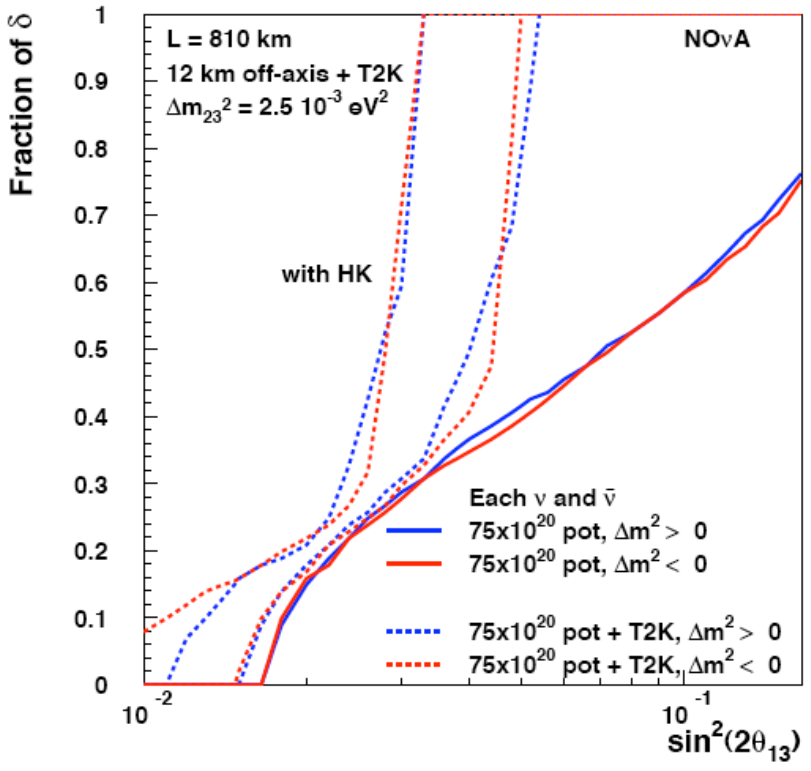


Corrected Plot

2 σ Resolution of the Mass Hierarchy

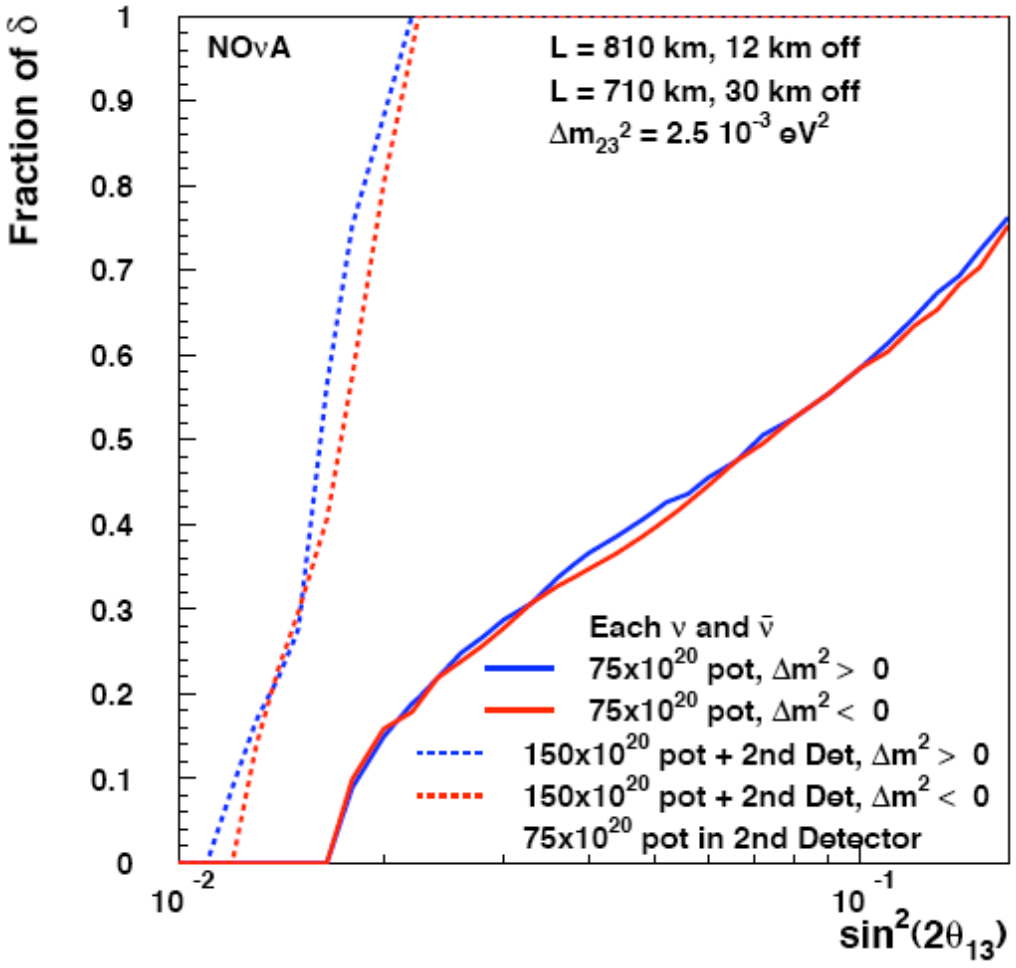


NOνA with T2K Phase 1



NOνA/PD with T2K Phase 2

2 σ Resolution of the Mass Hierarchy

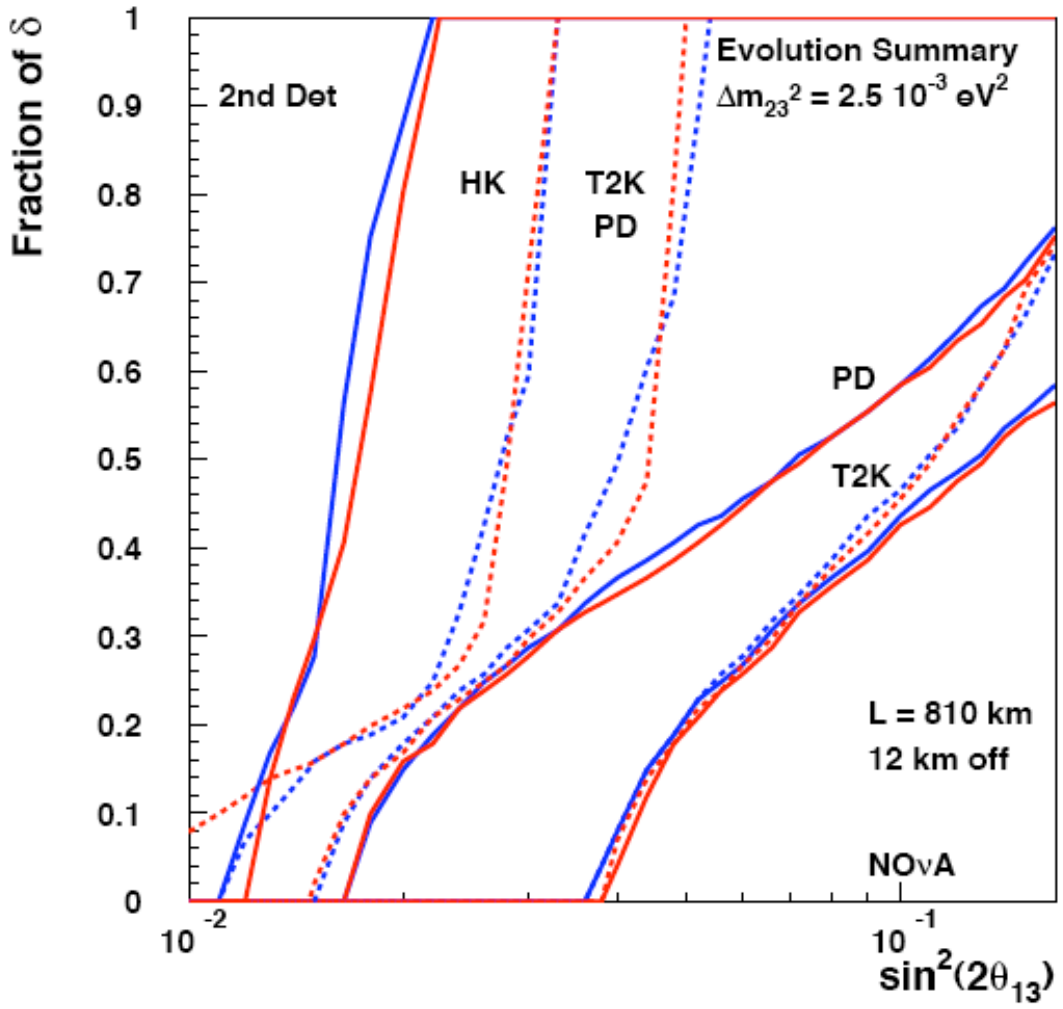


Scenario:

2 years into the PD run, realize the need for the 2nd off-axis detector. Build in 4 years, run for 6 years. Thus, 12 years running of NOνA with PD and 6 years of running the second detector.

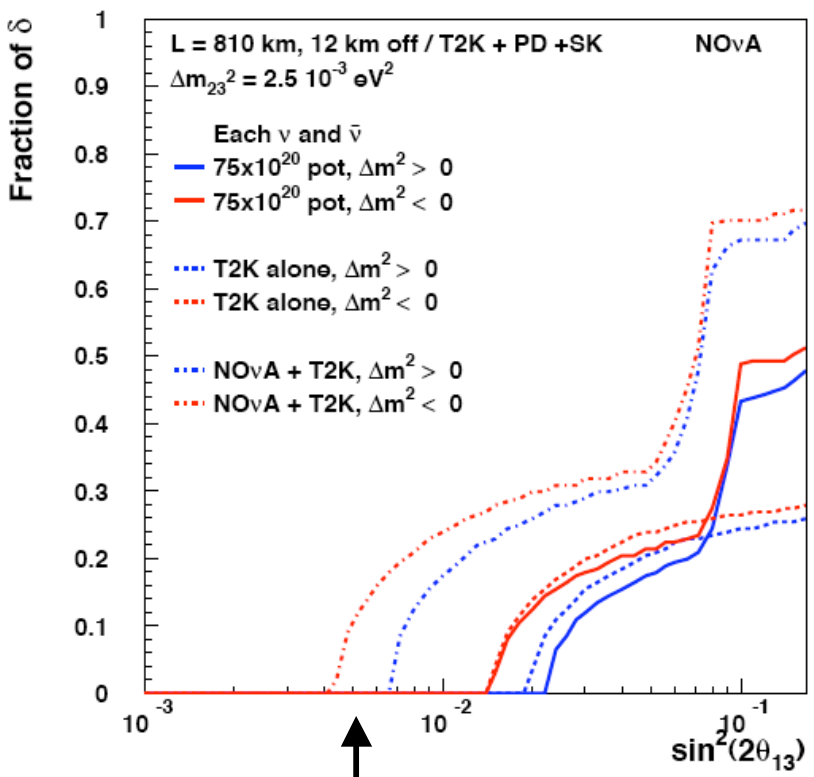
Several technologies possible for the 2nd detector. Use SK as a model for the calculation.

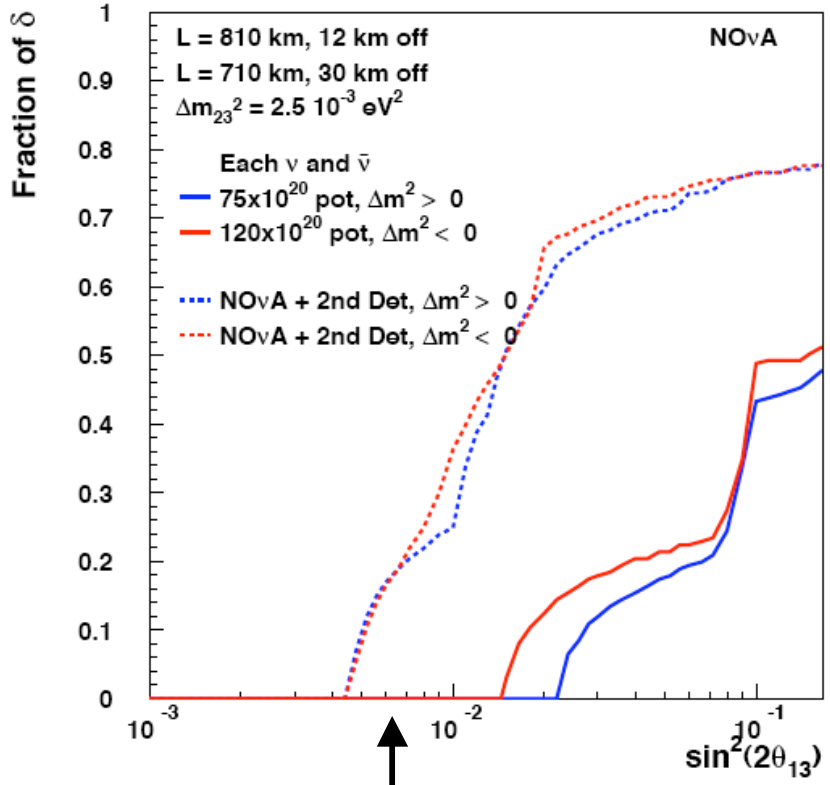
2 σ Resolution of the Mass Hierarchy



Summary plot

3 σ Determination of CP Violation



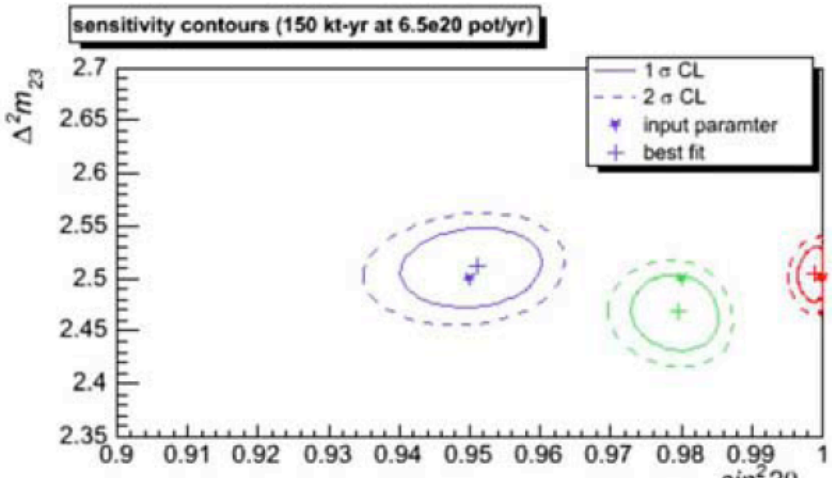


Not yet corrected

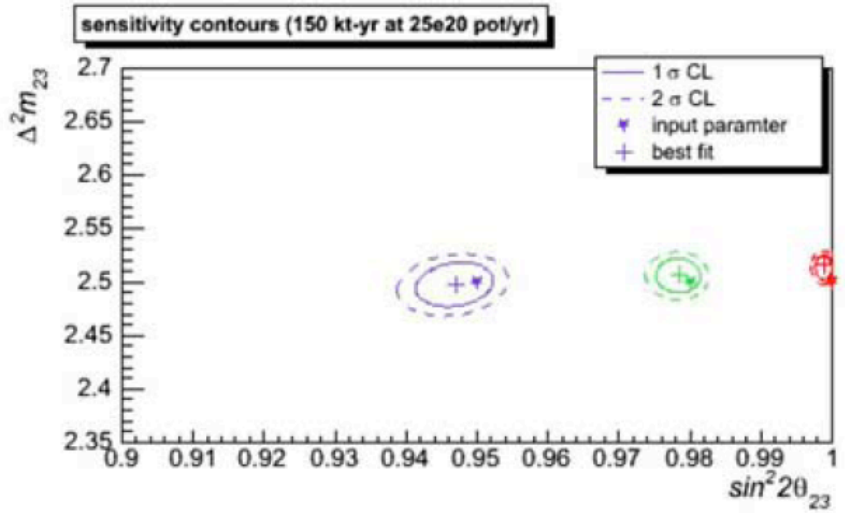
NOνA with upgraded T2K to SK

NOνA with 2nd NuMI off-axis detector

Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$

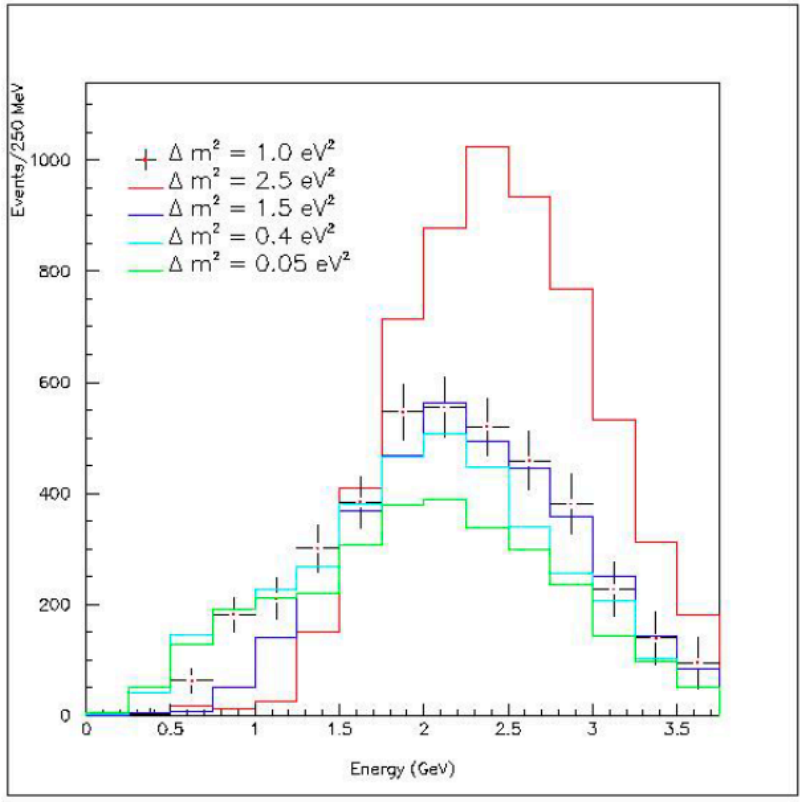


5-year ν run

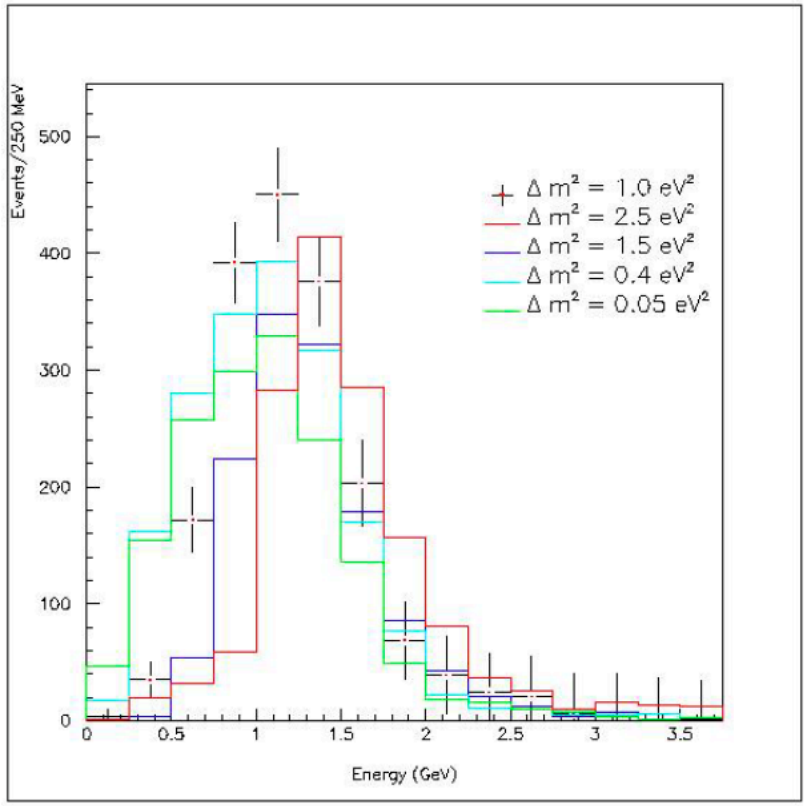


5-year ν run with Proton Driver

Study MiniBooNE Signal



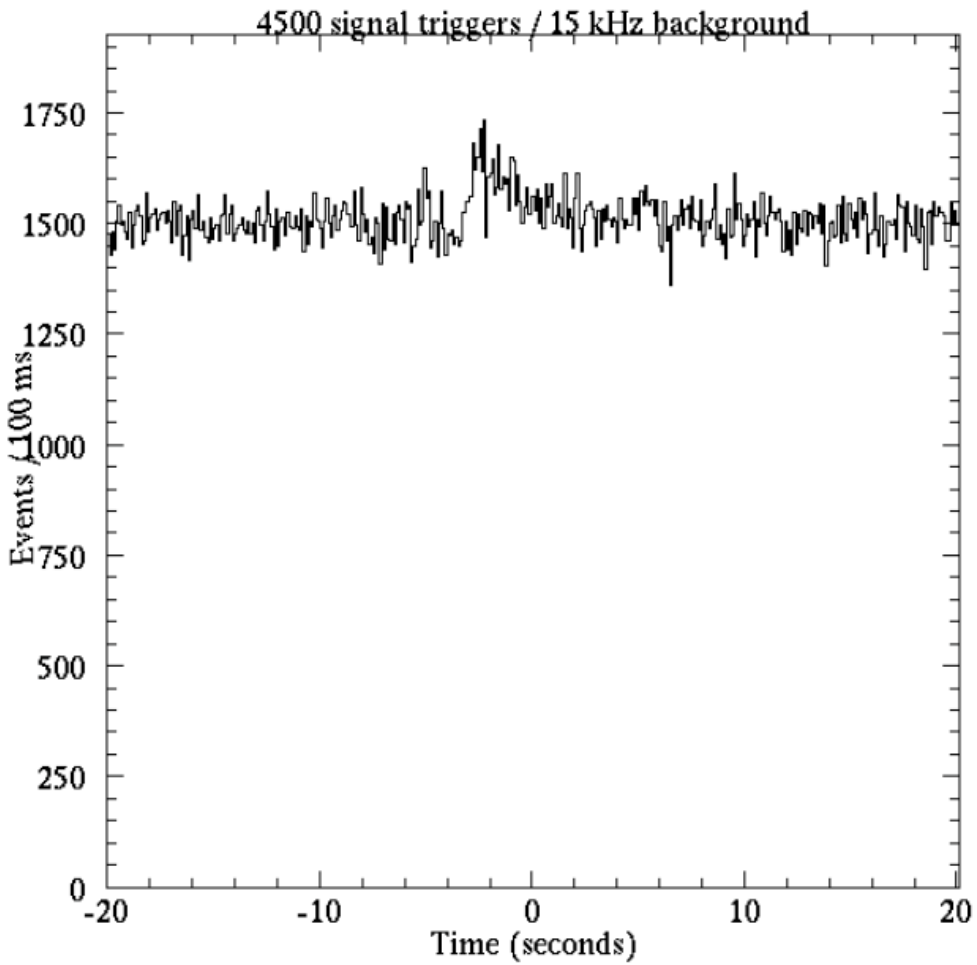
Site 1.5



Site 3

1-year ν run

Sensitivity to a Galactic Supernova



1800 events in the 1st second for a supernova 10 kps away

Letter from Witherell

- The Committee found that NOνA meets the criteria they developed last June and that it is the best approach to address the compelling neutrino physics questions ahead of us. They judged NOνA to be well designed, fully competitive, and complementary to other efforts. They also consider it to be the right platform for further steps in the evolving neutrino program worldwide. The Committee recommended Stage I approval.
- Organizing the best program of neutrino research with Fermilab's accelerators is critical to the strength of the particle physics program in the US and worldwide. I agree with the Committee's judgment that NOνA is the right experiment to anchor this program, and I agree that now is the time to act. I therefore grant Stage I approval to the NOνA experiment.

Developments since the PAC Meeting

- PAC Questions – tomorrow
- EPP2010
- NuSAG
- Conversations with Mike and Pier
- Outreach to Italian Groups
- Meeting with Ed Temple
- Project Office
- R&D Plan